IWEH. International Workshop on Environmental Hydraulics
Theoretical, Experimental and Computational Solutions
Valencia, 29th, 30th October 2009

ENVIRONMENTAL, ECOLOGICAL AND CULTURAL IMPACTS OF TIDAL BORES, BENAKS, BONOS AND BURROS

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Keywords: Tidal bores, theory, observations, environmental impact, ecological impact, cultural heritage, benak, bono, burro, turbulence, turbulent mixing.

Abstract. *A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during the spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary with low freshwater levels. Tidal bores are locally called mascaret, pororoca, benak, bono, burro and aegir. A tidal bore is associated with a massive mixing of the estuarine waters that stirs the organic matter and creates some rich fishing grounds. Its occurrence is essential to many ecological processes and the survival of unique eco-systems. The tidal bore is also an integral part of the cultural heritage in many regions: the Qiantang River bore in China, the Severn River bore in UK, the Dordogne River in France. In this contribution, the environmental, ecological and cultural impacts of tidal bores are detailed and discussed.*

1 INTRODUCTION

A tidal bore is a surge of waters propagating upstream as the tidal flow turns to rising and the flood tide rushes into a funnel shaped river mouth with shallow waters (Fig. 1). The bore forms during the spring tides when the tidal range exceeds 4 to 6 m and the estuary bathymetry amplifies the tidal range with a low freshwater level. It is estimated worldwide that over 400 estuaries are affected by a tidal bore, on all continents but Antarctica. A bore is a discontinuity of the water depth and it represents a hydrodynamic shock. The tidal bore has a significant impact on the environmental system and the ecology of the river mouth. Recent studies demonstrated in particular the significant impact of small tidal bores and of non-breaking undular surges on natural channels [27, 31, 32]. Surprisingly, the tidal bore remains a challenging research topic to theoreticians, and many hydrodynamic features remain unexplained.

The existence of a tidal bore is based upon a delicate balance between the tidal flow range, the freshwater river flow conditions and the channel bathymetry. Some simple theoretical considerations show that this balance may be easily disturbed by some changes in the boundary conditions and freshwater runoff. For example, a number of tidal bores disappeared because of river training, dredging and damming. Some man-made interventions led to the loss of several bores with often adverse impacts onto the estuarine eco-systems. The tidal bore of the Seine River (France) no longer exists after extensive training works and dredging; the Colorado River bore (Mexico) is drastically smaller after dredging as well as the damming of the river. Although the fluvial traffic gained in safety in both cases, the ecology of the estuarine zones were adversely affected. The tidal bore of the Petitcodiac River (Canada) almost disappeared after construction of an upstream barrage that yielded the elimination of several native fish species. The proposed construction of the Severn Barrage in UK is a major threat to one of the best documented tidal bores: the Severn River bore. The tidal bores do have a significant effect on the natural channels and their ecology. The tidal bore affected estuaries are the natural habitats of several fish species: e.g., in the Severn, Petitcodiac and Rokan Rivers. The tidal bores can be some major tourism attractions like in Canada, China, France and UK. Several tidal bores are regularly surfed by kayakers and surfers in Brazil, France and UK. The surfers aim for the longest distance and ride duration. Some bores have had a sinister reputation although they contribute to the cultural heritage.

The tidal bores were studied by hydraulic engineers and applied mathematicians for a couple of centuries. Major contributions included the works of Bazin [2], Barré de Saint Venant [1], Boussinesq [5], Benjamin and Lighthill [3], and Peregrine [44]. In his milestone paper, Adhémar Jean Claude Barré de Saint Venant (1797-1886) applied his famous equations to the tidal bore of the Seine River [1]. Dennis Howell Peregrine (1938-2007) observed many times the Severn River bore and his work on tidal bores was inspired by this majestic bore [44].

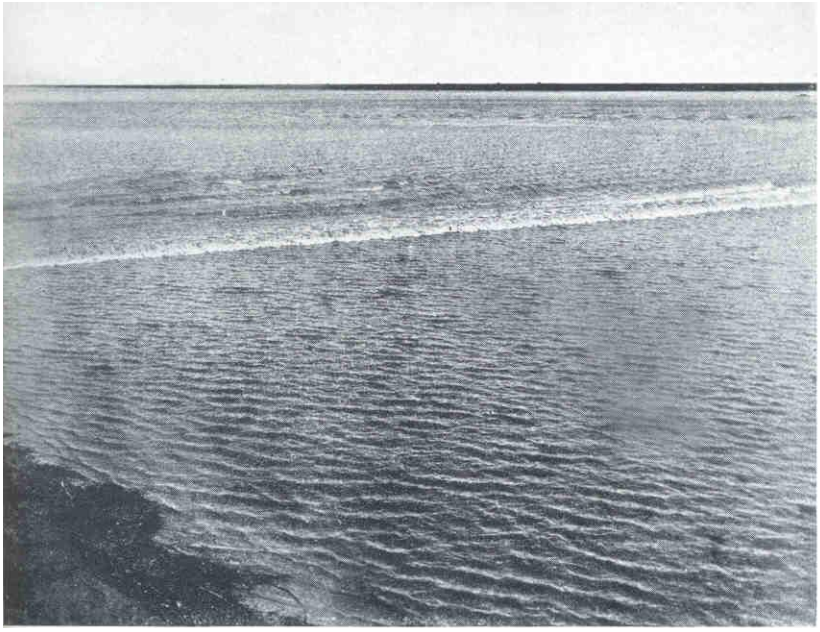
The origin of the word 'bore' is believed to derive from the Icelandic 'bara' (billow') indicating a potentially dangerous phenomenon: i.e., a tidal bore with a breaking roller [14]. In France, a tidal bore is called 'le mascaret' although some local names of tidal bores include 'le montant' (Garonne River, France), 'la barre' (Seine River, France), and 'le mascarin' (Vilaine, France). Other local names of tidal bores encompass the 'pororoca' (Amazon River, Brazil), the 'burro' (Colorado River, Mexico), the 'bono' (Rokan River, Indonesia), and the 'benak' (Batang Lupar River, Malaysia).

In this keynote paper, the author aims to share his enthusiasm and passion for the tidal bore. Some basic theoretical considerations are developed. The turbulence and turbulent mixing induced by a tidal bore are documented. The rumble noise of tidal bores is discussed based upon some field observations, before the interactions between tidal bores and mankind are discussed.

(A) Tidal bore ('pororoca') of the Rio Mearim (Brazil) in 205 (Courtesy of Antony Colas)

(B) Tidal bore ('bono') of the Kampar River (Indonesia) - Note the boats riding the bore front

(C) Tidal bore ('mascaret') of the Garonne River (France) 2 September 2008



(D) Small tidal bore ('burro') in the Colorado River estuary in 1904 (after Sykes [50]) - Looking downstream at the incoming breaking bore

Fig. 1 - Photographs of tidal bores

2 THEORETICAL CONSIDERATIONS

2.1 Basic principles

A tidal bore may occur when the tidal range exceeds 4 to 6 m and the funnel shape of the river mouth amplifies the tidal wave. The driving process is the large tidal amplitude. The tides are forced oscillations generated by the attractions of the Moon and Sun, and have the same periods as the motion of the Sun and Moon relative to the Earth. Every fourteenth day at full moon or new moon, the attraction forces of the Sun and Moon reinforce one another, and these conditions give the spring tide conditions. The tidal range may be locally amplified further by a number of factors including when the natural resonance of the bay and estuary is close to the tidal period [13, 43]. This coincidence implies that the general sloshing of the waters around the inlet or bay becomes synchronised with the lunar tides and amplifies their effect, yielding often the best tidal bores a couple of days after the date of the maximum tidal range.

When the sea level rises with time during the flood tide, the tidal wave becomes steeper and steeper, until it forms an abrupt front: the tidal bore. After the formation of the bore, there is an abrupt rise in water depth at the tidal bore front and the flow singularity may be analysed as a hydraulic jump in translation [7, 36]. The inception and development of a tidal bore may be predicted using the Saint-Venant equations and the method of characteristics. The flow properties immediately upstream and downstream of the tidal bore front must satisfy the continuity and momentum principles [25, 47]. Considering a tidal bore travelling in a river section, the bore front propagates upstream with a celerity U (Fig. 2). The same tidal bore is seen by an observer running alongside the bore at a speed U as a quasi-steady flow situation: the hydraulic jump in translation. The integral form of the equations of conservation of mass and momentum gives a series of relationships between the flow properties in front of and behind the tidal bore front:

(1) $$(V_1 + U) \times d_1 = (V_2 + U) \times d_1$$

(2) $$\frac{1}{2} \times \rho \times g \times (d_2{}^2 - d_1{}^2) = \rho \times (V_1 + U) \times d_1 \times (\beta_1 \times (V_1 + U) - \beta_2 \times (V_2 + U))$$

where V is the flow velocity positive downstream towards the river mouth, d is the water depth, ρ is the water density, g is the gravity acceleration, β is a momentum correction coefficient, the subscript 1 refers to the initial flow conditions and the subscript 2 refers to the new flow conditions (Fig. 2). Herein d_1 and d_2 are respectively the flow depths immediately before and after the tidal bore passage. Note that Equation (2) is based the assumption of hydrostatic pressure distribution in front of and behind the bore front, the friction losses are neglected and the river bed is assumed to be horizontal. The combination of Equations (1) and (2) yields the classical result:

(3) $$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8 \times Fr_1{}^2} - 1\right)$$

where Fr_1 is the tidal bore Froude number:

(4) $$Fr_1 = \frac{V_1 + U}{\sqrt{g \times d_1}}$$

The tidal bore Froude number Fr_1 is always greater than unity and the term (Fr_1-1) is a measure of the strength of the bore. If the Froude number Fr_1 is less than unity, the tidal wave cannot become a tidal bore. Equations (1) and (2) form a system of two equations with five variables (d_1, d_2, V_1, V_2, U). Typically the upstream conditions (V_1, d_1) are known and one more boundary condition is required [25].

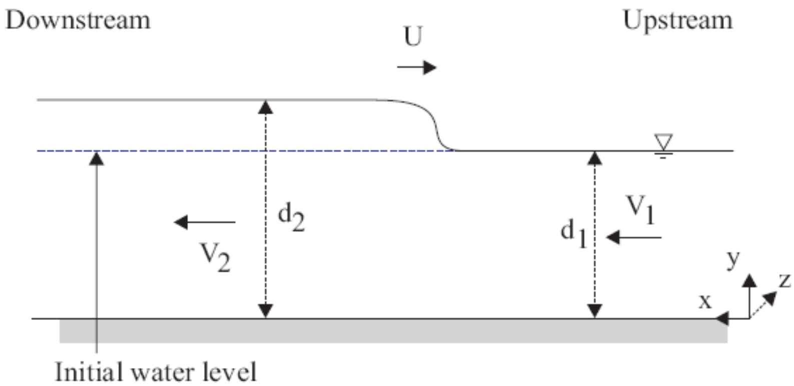


Fig. 2 - Definition sketch of a tidal bore propagating upstream

2.2 Undular tidal bores

The shape of the tidal bore is directly linked with its Froude number Fr_1. An undular tidal bore is observed for a bore Froude number between 1 and 1.5 to 1.8. For larger Froude numbers, a breaking bore takes place. Practically the very large majority of tidal bore occurrences have an undular shape: i.e., the leading wave followed by a train of well-developed undulations called whelps (Fig. 3). For example, the Equipe Cousteau photographed the 'pororoca' of the Amazon River about 10 nautical miles before it reached the river mouth [42]. There were more than 30 waves, each 2-3 m high with 20-30 m between crests, and extending behind the horizon with an estimated visibility of 20 nautical miles. Figure 3 shows an example of an undular tidal bore. Immediately behind the bore front, the wave train presents a pseudo-periodic, undular profile, although the observations show also the development of "semi-chaotic" patterns with increasing time. The field observations indicate also the long-lasting effects of the wave motion also called 'whelps', sometimes more than 20 to 30 minutes after the tidal bore passage. This aspect is well-known to surfers and kayakers who can experience some difficulties to come back ashore after surfing.

Fig. 3 - Undular tidal bore of the Dordogne River (France) on 27 September 2008 - Looking downstream at the incoming bore - The surfer is riding in front of the third wave crest

Considering an undular bore in the system of co-ordinates in translation with the bore front, the flow is quasi-steady and the free-surface profile is stationary. For a two-dimensional incompressible flow, the differential form of the equation of conservation of mass is:

(5) $$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial x} = 0$$

where V_x is the longitudinal velocity component positive downstream and V_y is the vertical velocity component positive upwards. Since the fluid is incompressible, the stream function ψ exists and the velocity components equal respectively $V_x = -\partial\psi/\partial y$ and $V_y = \partial\psi/\partial x$. The condition of irrotational flow motion is a Laplace equation in terms of the stream function: $\Delta\psi = 0$, and the boundary conditions are: (a) $\psi(y=0) = 0$ at the channel bed, (b) $\psi(y=d) = -q$ at the water free-surface where $q = (V_1+U)\times d_1$ is the water flow rate per unit width in the quasi-steady flow analogy system of co-ordinates (Eq. (1)), and (c) the Bernoulli principle:

$$\frac{(V_x{}^2 + V_y{}^2)}{2} + g \times y + \frac{P}{\rho} = \text{constant}$$

with y the vertical elevation (y = 0 at the bed), and P the local pressure. Note that, with the above sign convention, the flux q is positive for a tidal bore propagating upstream. Using the continuity equation, the Navier-Stokes equation for an ideal fluid in the y-direction becomes:

(6) $$V_x{}^2 \times \frac{\partial(V_y / V_x)}{\partial x} = -\frac{1}{\rho} \times \frac{\partial P}{\partial y} - g$$

When the streamline curvature is non negligible, the pressure gradient departs from the hydrostatic pressure gradient ($\partial P/\partial y = -\rho \times g$) and Equation (6) gives an expression for the pressure deviation caused by the free-surface curvature [40]. Assuming a linear vertical distribution of the vertical velocity component, the equation of conservation of mass implies that the vertical velocity component at the free-surface (y = d) equals:

(7) $$\frac{V_y\,(y=d)}{V_x\,(y=d)} = \frac{\partial d}{\partial x}$$

with d the local flow depth.

The variation of pressure field in response to the surface curvature(Eq. (6)) gives a differential equation in terms of the flow depth d and depth-averaged longitudinal velocity $\overline{V}$. For an ideal fluid in a horizontal channel, it yields:

(8) $$\frac{\partial}{\partial x}\left(\overline{V}^2 \times d + \frac{1}{2} \times g \times d^2 + \frac{1}{3} \times \overline{V}^2 \times d \times \left(d \times \frac{\partial^2 d}{\partial x^2} - \left(\frac{\partial d}{\partial x}\right)^2\right)\right) = 0$$

Note that a velocity correction coefficient was dropped in the uppermost left term for clarity. In the system of co-ordinates of the quasi-steady flow analogy, the integration of Equation (8) has a solution:

(9) $$\left(\frac{\partial d}{\partial x}\right)^2 = 6\times g\times\left(-M\times d-\frac{1}{3}\times d^3+\frac{q}{g}-E\times d^2\right)=0$$

where M and E are respectively the momentum function and the specific energy [40]. The M- and E-functions are defined for the general case of a non hydrostatic pressure distribution and non-uniform velocity profile:

(10) $$M=\int_0^d\left(\frac{P}{\rho\times g}+\frac{{V_x}^2}{2\times g}\right)\times dy$$

(11) $$E=\frac{1}{d}\times\int_0^d\left(y+\frac{P}{\rho\times g}+\frac{{V_x}^2+{V_y}^2}{2\times g}\right)\times dy$$

The periodic wave solution of Equation (9) is called a cnoidal wave function because it takes the form of the square of the Jacobian elliptic function cn [20, 21, 53]. Some typical free-surface profiles are presented in Figures 4 and 5. Figure 4 shows the water depth as a function of the time at a fixed location, while Figure 5 presents the water elevation as a function of the longitudinal distance at a given time. The measurements highlight the pseudo-periodic shape of the free-surface undulations. In Figures 4 and 5, the data are compared with a sinusoidal curve and cnoidal wave function. Herein, each function was fitted for each half-wave length between a crest/trough and the adjacent trough/crest. Altogether there is a reasonable agreement between the data and mathematical functions, although neither the linear wave theory nor the Boussinesq equations capture the asymmetrical wave shape nor the fine details of the free-surface profile shape. The findings are consistent with an earlier study of relatively large amplitude shallow water waves [33].

Noteworthy, the agreement between the free-surface data and cnoidal wave function is best achieved using the parameter of the elliptic function $m > 0.5$ between a wave crest and trough, while $m < 0.5$ between a wave trough and crest. For $m = 0$, the cnoidal wave function equals the sinusoidal profile and more generally the nonlinearity causes little departure from the linear wave theory for small values of m. As m increases, the crest becomes more peaky and the trough shallower. The experimental observations highlight the asymmetry of the free-surface undulations, with some differences in wave shape between a crest and trough, and between a trough and the next wave crest. The undulation asymmetry was already noted in the stationary undular hydraulic jumps in terms of both the free-surface profile and the vertical distributions of pressure and velocity [19].

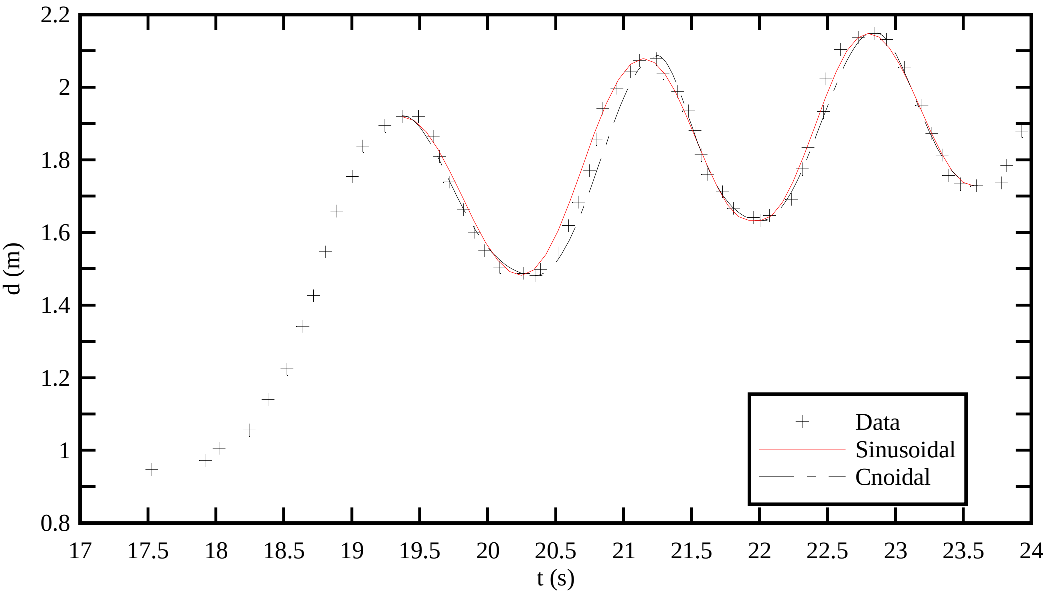


Fig. 4 - Free-surface profile of an undular tidal bore: time-variation of the flow depth for the Dee River tidal bore on 22 September 1972 (Data: Lewis [34]) - Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal)

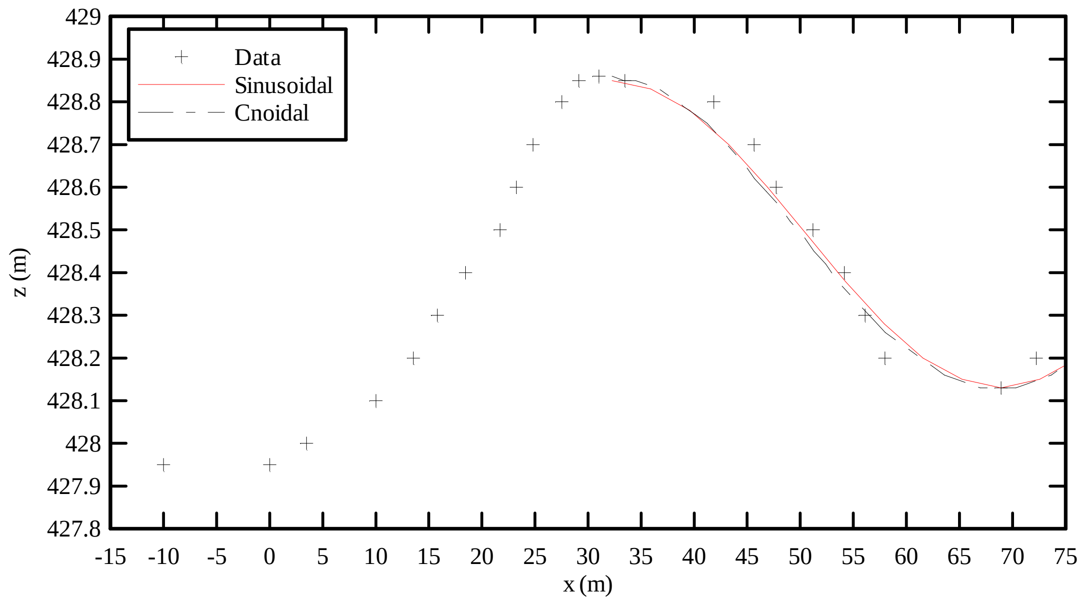


Fig. 5 - Free-surface profile of an undular tidal bore: longitudinal variation of the water elevation in an undular positive surge in the Oraison power plant intake channel (Data: Ponsy and Carbonnell [45]) - Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal)

3 TURBULENT FLOW FIELD

The visual observations of tidal bores highlight the turbulent nature of the surging waters. The tidal bore induces a strong turbulent mixing in the estuarine zone, and the effects may be felt along considerable distances. The velocity observations indicate a rapid deceleration of the flow associated with the passage of the bore. In the Dee River estuary, some two-dimensional velocity measurements were conducted in an undular bore; after the front passage, the velocity record shows about 30 undulations in about 45 s and the velocity oscillation pattern is consistent with typical observations of "*wave period* [...] *just less than 2 seconds for a very weak undular bore dropping to about 1 sec for the whelps following a stronger perhaps partly breaking bore*" at Saltney Ferry bridge (Huntley, D. 2003, Person. Comm.; Jones, J.E. 2005, Pers. Comm.). A similar pattern is observed in the Daly River undular bore, although the irregular channel cross-section was responsible for some complicated whelp motion [55]. In a breaking tidal bore, a brutal flow deceleration is observed at the passage of the bore roller [49].

Some recent free-surface and turbulent velocity measurements were conducted in large-size laboratory facilities with some detailed temporal and spatial resolutions [8, 9, 27, 31, 32]. A typical example is presented in Figure 6 where V_x is the longitudinal velocity component positive downstream, V_y is the vertical velocity component positive upstream, V_y is the transverse horizontal velocity component, d_1 is the initial water depth, V_1 is the initial flow velocity positive downstream, V_2 is the flow velocity immediately behind the tidal bore, and y is the vertical elevation. The experimental data indicate systematically that the arrival of the tidal bore and the sudden increase in water depth yield a sudden deceleration to satisfy the conservation of mass. In a natural river, a flow reversal ($V_x < 0$) is often observed. The longitudinal velocities are characterised by a rapid flow deceleration at all vertical elevations, while large fluctuations of longitudinal, transverse and vertical velocity components are observed beneath the tidal bore. The tidal bore is simply a shock characterised by a sudden change in the velocity and pressure fields [35]. The shock is followed by a highly turbulent flow motion with significant fluctuations of all velocity components.

When the velocity measurements are conducted with a relatively fast sampling rate (above 20 to 25 Hz), the turbulent stresses, also called Reynolds stresses, may be estimated with some accuracy. These are the stresses in the water causing the random turbulent fluctuations in fluid momentum; they characterise a transport effect resulting from turbulent motion induced by velocity fluctuations with its subsequent increase of momentum exchange and of mixing. The experimental data sets show some large turbulent stresses, and turbulent stress fluctuations beneath the tidal bore and ensuing whelp motion. The measurements indicate that the Reynolds stress magnitudes are significantly larger than in the initially steady flow prior to the tidal bore. Quantitatively, the levels of turbulent stresses are one to two orders of magnitude larger than the critical threshold for sediment motion, in terms of both bed load and suspension. Figure 7 presents the time-variations of a dimensionless component of the Reynolds stress tensor beneath a breaking bore. The results illustrate that a tidal bore induces a very strong mixing in the channel, and the classical mixing theories do not account for such type of shocks. Some bed erosion may take place during the tidal bore passage, and the eroded material as well other scalars are advected with the "whelps" and secondary wave motion behind the tidal bore front. This is consistent with the very-strong turbulent mixing, observed visually in the tidal bore affected estuaries, that is associated with the accretion and deposition of sediment materials in the upper estuarine zone.

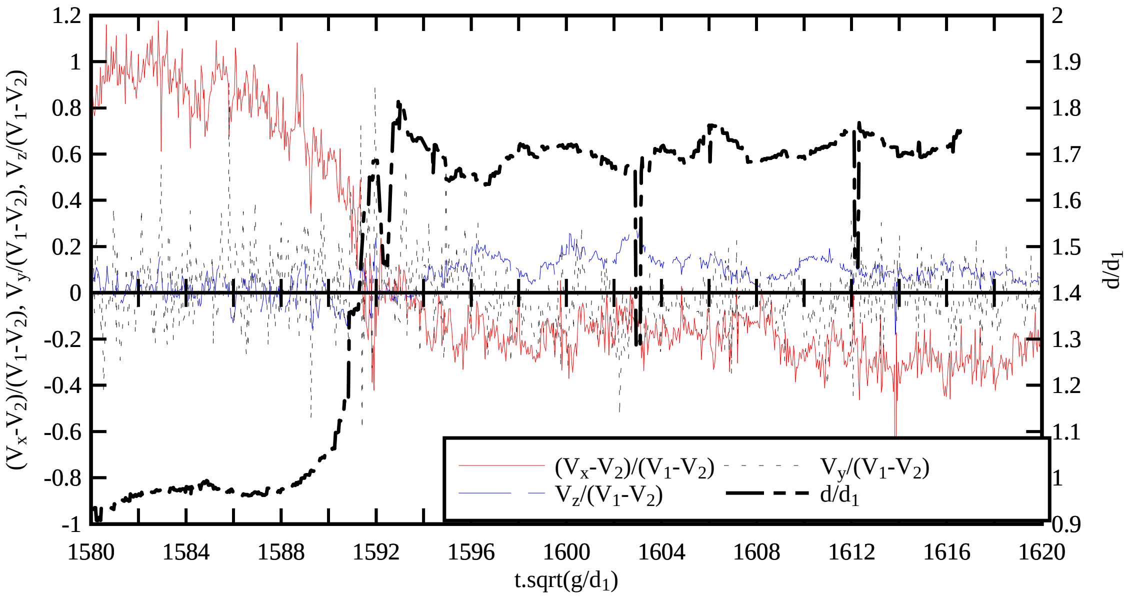


Fig. 6 - Instantaneous longitudinal, vertical and transverse velocity measurements beneath a breaking tidal bore - Data: Chanson [8], d_1 = 0.1388 m, Fr_1 = 1.50, y/d_1 = 0.150, y/d_1 = 0.150

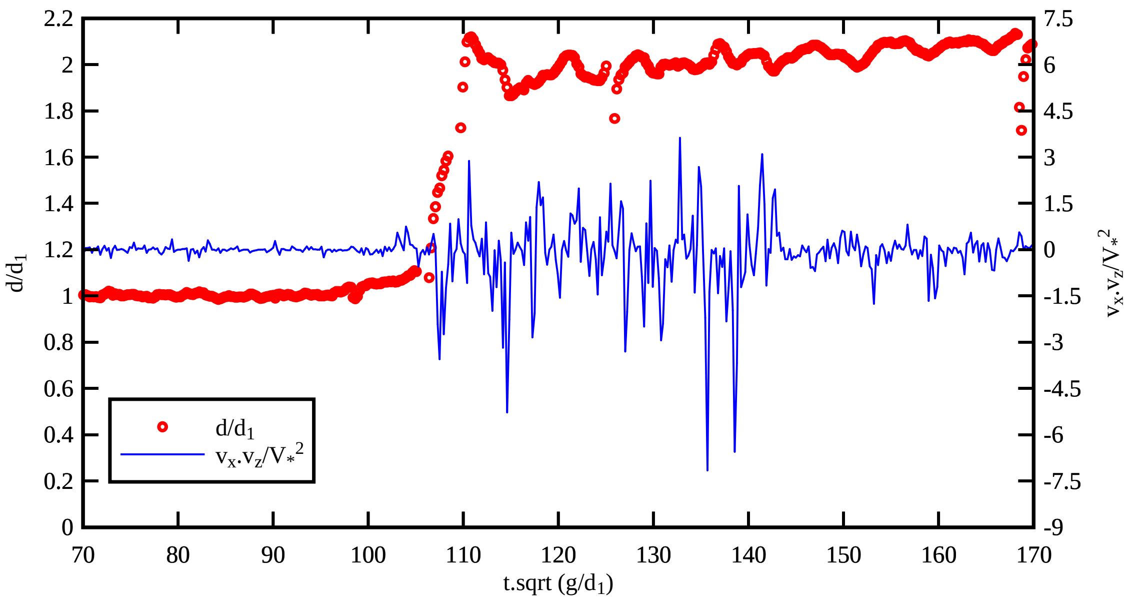


Fig. 7 - Instantaneous turbulent Reynolds stress $(v_x \times v_z)/V_*^2$ beneath a breaking tidal bore - Data: Koch and Chanson [32], d_1 = 0.080 m, Fr_1 = 1.8, y/d_1 = 0.728, V_* = 0.044 m/s

The velocity measurements suggest some energetic turbulent events beneath and after the tidal bore front (Fig. 6 & 7). These are best seen by some sudden and rapid fluctuations of the transverse and vertical velocity data (Fig. 6), while some recent numerical modelling highlights the production of large turbulent eddies beneath the bore front and their upstream advection behind the bore [22]. These vortical structures remain near the bed as the bore propagates upstream and the presence of these persisting turbulent structures indicate that a great amount of sediment matters is placed in suspension and advected upstream. Both physical and numerical modelling studies show some large transverse and vertical velocity fluctuations implying the existence of transient secondary currents behind the bore front. The evidences of turbulence "patches" encompass both undular and breaking bore conditions, and some simple considerations implies that the vorticity production rate is proportional to $(Fr - 1)^3$ [27]. The vorticity "clouds" behind a tidal bore are a feature of tidal bores that are linked with some secondary current motion and are enhanced by the natural, non-prismatic channel bathymetry. The macro-scale turbulence is advected behind the bore front, contributing to the energetic turbulent velocity fluctuation periods observed in the Daly River with some surface "*clockwise and counterclockwise rotating eddies*" about 20 minutes after the tidal bore passage [55].

4 RUMBLE NOISE OF TIDAL BORES

A tidal bore creates a powerful roar that combines the sounds caused by the turbulence in the bore front and whelps, entrained air bubbles in the bore roller, sediment erosion beneath the bore front and of the banks, scouring of shoals and bars, and impacts on obstacles. The bore rumble is heard far away because its low frequencies can travel over long distances. During his expedition in the Qiantang River mouth, Captain Moore heard the first murmur of the tidal bore one hour before it reached his Pandora ship. In the Baie du Mont Saint Michel, the tidal bore is often heard 25 to 30 minutes before the bore reaches the spectators. In the Severn River, the bore may be heard more than 20 minutes ahead during the night. Some animals are more sensitive to the tidal bore sounds than the human ear. When the bore closes in, the rumbling noise disorientates some species. In the Baie du Mont Saint Michel, sheep have been outrun and drowned by the tidal bore. In Alaska, moose have tried unsuccessfully to outrun the bore [39]. In most situations, the animals are panicked with the deafening noise of the bore although they could run faster than the bore front.

The atmospheric sounds of a tidal bore event were recorded in the Baie du Mont Saint Michel (France) using a passive acoustic technique [10]. Figure 8 presents a photograph of the breaking bore at the measurement location, but taken a few weeks later. The acoustic measurements lasted for about 4 minutes, and the record presented three successive periods with distinct acoustic characteristics: (a) the tidal bore approaching the Pointe du Grouin du Sud with a sound amplitude increasing with time, (b) the passage of the tidal bore in front of the rocky promontory with powerful noises, and (c) the upstream propagation of the tidal bore with the flood tidal flow past the promontory. When the tidal bore passed around the rocky promontory (2nd period), the noise was in average five times louder than during the incoming tidal bore phase (1st period). The results of the record spectral analysis are summarised in Figure 9. In each spectrum, a dominant frequency is observed and ranges from 74 to 131 Hz. All the values correspond to a low pitch sound or rumble within the entire audible range of sounds for a human ear. During the first period, the tidal bore was a breaking bore advancing in the main channel and over sand banks and mudflats. The low-frequency sound (76-77 Hz) may be considered a characteristic feature of the advancing roller, caused by the turbulence and entrained bubbles in the roller. For the second period, the tidal bore impact onto the rocky promontory was an energetic process generating very loud noises of a higher pitch that corresponded to a dominant frequency around 113-131 Hz. During the third period, the sounds were a combination of the departing tidal bore together with the impact of the flood flow on the promontory rocks. This yields a slightly flatter, broader acoustic spectrum as shown in Figure 9.

In Figure 9, the acoustic signature of the tidal bore is compared with the sound record of the bore whelps and flood flow measured the same location about 4 to 5 minutes after the tidal bore passage. The sounds consisted of a combination of the noises of the flood flow crashing on the rocks of the promontory, of the flood flow past the Pointe du Grouin du Sud, and of the tidal bore in the far background. The recorded sounds were powerful and quite violent. Indeed, in Figure 9, the second loudest sound record is that of the whelps and flood flow.

In a breaking bore, some large scale vortical structures are generated at the roller toe and advected downstream behind the bore [27]. The bore roller is characterised by some air bubble entrainment at the toe and advection in the roller [32]. Using a model of a spilling breaker, Prosperetti [46] showed that bubble generation at the roller toe can amplify the pressure oscillations induced by the large-scale turbulence. In a bubble cloud, the coupled oscillations of the bubbles have a lowest mode frequency much smaller than that of individual bubbles. In first approximation, the lowest natural frequency f_{cloud} of the bubbly cloud is:

$$f_{cloud} = \frac{1}{L} \times \sqrt{\frac{P}{\rho \times \alpha}} \tag{12}$$

where P is the ambient pressure, ρ is the water density, L is the bubble cloud characteristic length and α is the void fraction [46]. The natural frequency of a bubble cloud is inversely proportional to $\alpha^{1/2}$ and to the cloud characteristic size. Equation (12) is presented in Figure 10 as function of the void fraction α and cloud dimension L. In a tidal bore, the bubbles are entrapped in large-scale vortical structure and a characteristic dimension is the roller height. Considering a bore height between 0.7 and 1 m like in the Baie du Mont Saint Michel, the lowest natural frequency of the bubbly cloud would be about 30 to 140 Hz for void fractions between 1 and 10%. Note that Equation (12) implies that large tidal bores would generate lower pitch sound than the small ones.

The application of this analysis to the tidal bore roller yields a dominant frequency within the observed frequency ranges (Fig. 9), and the finding suggests that the air bubbles entrapped in the large-scale eddies of the tidal bore roller are acoustically active and play the dominant role in the rumble sound generation. Note also that the sounds generated by the tidal bore have a low-pitch comparable to the sounds generated by bass drums and locomotive trains. In tidal channels and under waves, the sediment motion by bed load induces particle collisions that transmit an acoustic pulse to the water with characteristic frequencies between 1.5 and 400 kHz [38, 52]. While the sediment motion is not the dominant cause of the tidal bore rumble noise, it might explain the secondary peak about 8-10 kHz in Figure 9.

Fig. 8 - Breaking bore in the Baie du Mont St Michel (France) on 19 October 2008 at the Pointe du Grouin du Sud

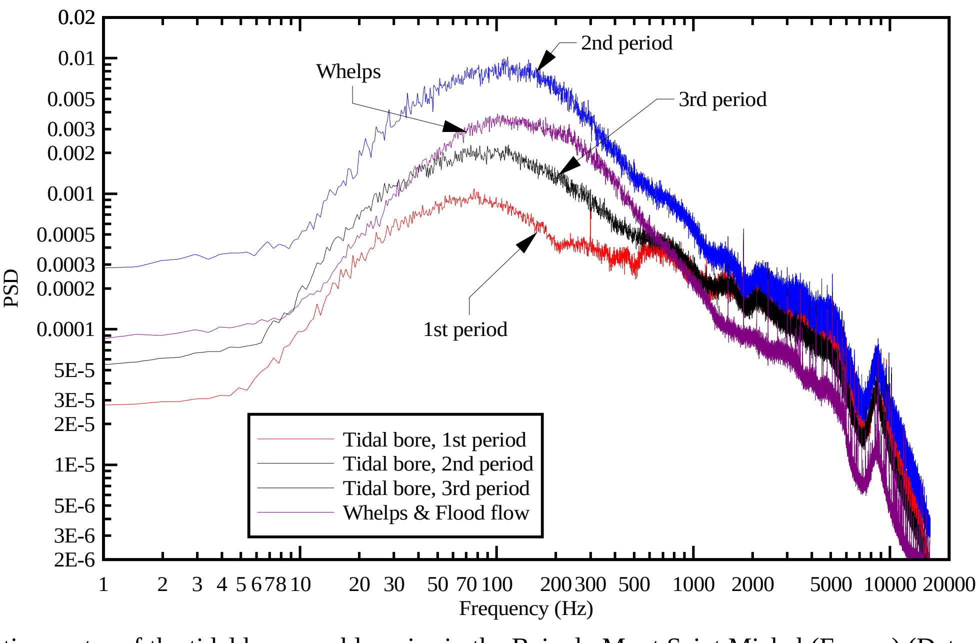


Fig. 9 - Acoustic spectra of the tidal bore rumble noise in the Baie du Mont Saint Michel (France) (Data: Chanson [10]) - Comparison with the whelp flow noise

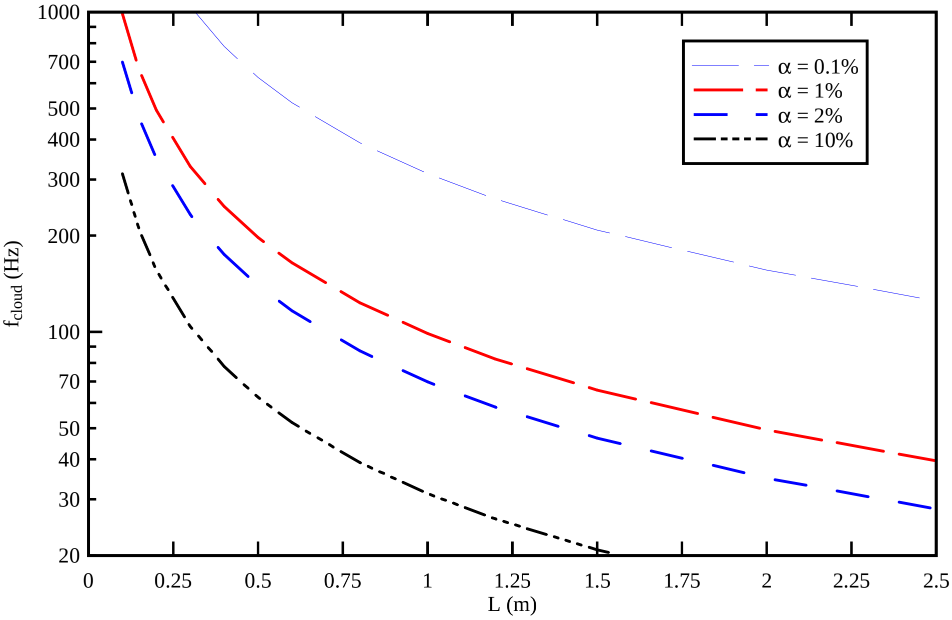


Fig. 10 - Lowest natural frequency of a bubble cloud as a function of the bubble cloud characteristic length and void fraction

5 IMPACT OF TIDAL BORES ON ESTUARINE PROCESSES

5.1 Presentation

The field studies demonstrate that the arrival of the tidal bore is always associated with some intense mixing and with the upstream advection of the suspended material. The effects of tidal bores on sediment processes were studied in Alaska, China and France in particular, among which the works of Chen et al. [11] in the Hangzhou Bay and Qiantang River estuary, of Tessier and Terwindt [51] in the Baie du Mont-Saint-Michel, and of Greb and Archer [24] in Alaska. In 1274 AD, the Chinese writer Chien Yueh-yu described the impact of the Qiantang River bore on the river channel: "*the turbid waters are piled up and the water behind comes on in a mass, and then it busts over the sand-flats with fury and boiling rage and tremendous sound*" [41]. In the Baie du Mont Saint Michel (France), the author observed the formation of a new main channel by the tidal bore when it cut a channel meander between Pointe du Grouin du Sud and Roche Torin; the new incision became the main channel by the next tide. The event was followed by intense bed form motion processes and standing waves. The anecdotal evidences are numerous, from Branner [4] in the Amazon (Brazil) to Wolanski et al. [54, 55] in the Ord and Daly Rivers (Australia). The field observations are supported by experimental measurements of turbulent shear stresses during and after bore front passage [27, 31, 32]. In undular tidal bores, the sediment suspension is further sustained by strong wave motion of the whelps for relatively long periods after the bore passage, facilitating the upstream advection of the solid matter within the flood flow behind the bore.

The evidences of turbulent mixing induced by tidal bores are plenty and sometimes challenging. In the Mersey River (UK) and Rio Mearim (Brazil), the salinity measurements during and after tidal bore events showed sharp jumps in salinity and temperature several minutes after the bore passage with a delay depending upon the sampling site location and depth [18, 30]. In the Daly River (Australia) and the northern Branch of the Changjiang River Estuary, some major re-suspension of sediments occurred several minutes after the passage of the tidal bore [12, 55]. In the Daly River (Australia), a period of very strong turbulence was observed about twenty minutes after the bore passage and lasting for about three minutes [55]. The anecdote is challenging because it suggests the upstream advection of a "cloud" of turbulence and vorticity behind the bore that is characterised by very turbid and murky waters and extends for a considerable distance.

The tidal bores do cause some major damage to river banks and create navigation hazards in tidal bore affected estuaries. Both the Seine and Qiantang River tidal bores were renowned for their "temperamental" behaviour. In modern times, the Qiantang River banks were overtopped by the tidal bore and dozens of drownings in the bore flow are reported each year. Other tragic evidences of drownings in tidal bores and "whelps" include numerous human losses in the Colorado River (Mexico), Bamu and Fly Rivers (PNG), and Seine River (France). Related incidents included the damage to scientific equipments in the Rio Mearim (Brazil), in the Daly River (Australia), and in the Dee River (UK). For example, "*during this* [...] *deployment, the (ADCP) instrument was repeatedly buried in sediment after the 1st tidal cycle and had to be dug out of the sediment, with considerable difficulty, at the time of recovery*" (Simspon et al. [49], in the Dee River); "*on 30 January 1991, one sawhorse and instrument tumbled along the bottom for 1.4 km with* *currents exceeding 3 m.s^{-1}, was buried in a sand bank, and had to be abandoned*" (Kjerfve and Ferreira [30], in the Rio Mearim); "*about 20 min after the passage of the bore the two aluminium frames at site C were toppled.* [...] *A 3-min-duration patch of macro-turbulence was observed.* [...] *This unsteady motion was sufficiently energetic to topple moorings that had survived much higher, quasi-steady currents of 1.8 ms^{-1}*" (Wolanski et al. [55], in the Daly River). The experiences cannot be dismissed lightly.

The tidal bores have a significant impact on the eco-systems. The tidal bore affected estuaries are the natural habitat, as well as the feeding zone and breeding grounds of several forms of wildlife. The evidences regroup both scientific and anecdotic observations. In Brazil, the pororoca sets organic matters into suspension and the estuarine zone is the feeding grounds of piranhas. In Alaska and in France, several birds of prey are fishing behind the tidal bore front and next to the banks: e.g., bald eagles in Alaska and buzzards in France. Visual observations in Alaska and France showed a number of fish being ejected above the bore roller by the flow turbulence. The author saw it several times in the Dordogne River. In Alaska, the eagles catch these fish jumping off and projected upwards above the tidal bore roller. Several large predators feed immediately behind the tidal bore during its upstream progression. These include the beluga whales in Alaska (Turnagain Inlet), the seals in the Baie du Mont Saint Michel, the sharks in Queensland (Styx River and Broadsound) and the crocodiles in northern Australia and Malaysia (Daly and Batang Lupar River) (Fig. 10 & 11). The predators take advantages of the smaller fish that lost their directional awareness in the bore turbulence. In the Dordogne River (France), the fishermen profit of the tidal bore to fish shortly before and immediately after the bore passage and of the fast flowing flood flow. The tidal bore estuarine zones are indeed the breeding grounds of several fish species. These include the sturgeons and the elvers in the Severn River (UK), and the striped bass in the Bay of Fundy (Canada). In Sumatra, the Rokan River estuary is renowned for its abundance of fish, the organic matter being continually brought by the river while the turbulent mixing and aeration induced by the tidal bore contribute to the growth of many species of finfish and shrimps [6]. In China, Dai and Zhou [16] related the stories of local fishermen running with the tidal bore along the water line to catch "*fishes floating at the surface that were disabled by the impact of the bore*". These authors stressed the dangerous nature of the fishing: "*if the fisherman could not keep up with the bore, he might be drowned*".

Some animals are also seen playing with the tidal bore. In the Dordogne, Garonne and Severn Rivers, the swans are sometimes observed surfing the bore front. The author himself saw several times the swans riding the tidal bore of the Garonne and Dordogne Rivers.

Fig. 10 - Saltwater crocodile following the tidal bore of the Daly River, Australia in September 2002 (Courtesy of Dr Eric Wolanski)

Fig. 11 - Female seal rescued in the Baie du Mont Saint Michel and released in 2007 (Courtesy of Nathanaëlle Eudes) - These seals often follow the tidal bore for feeding

5.2 Fragility of the tidal bores

The existence of a tidal bore is based upon a fragile hydrodynamic balance between the tidal amplitude, the freshwater level and velocity, and the river channel bathymetry. This balance may be easily disturbed by changes in boundary conditions and freshwater inflow. This is illustrated by the application of the momentum principle to the tidal bore (Eq. (1) and (2)) and the relationship between the flow depths upstream and downstream of the tidal bore front (Eq. (3)). Despite its apparent simplicity, Equation (3) does explain the occurrence, or disappearance, and the strengthening, or weakening, of a tidal bore, as well as its changes in shape and appearance during its propagation. A tidal bore does not exist for a bore Froude number less than unity ($Fr_1 < 1$). When $Fr_1 < 1$, the tidal wave propagates upstream as a gentle surface slope and there is no discontinuity in flow depth, hence no tidal bore. A tidal bore does not occur during a river flood when the initial water depth d_1 is large, nor when the tidal range is small (i.e. neap tides). The strength of a tidal bore is proportional to the Froude number minus unity (Fr_1-1). For example, for a Froude number slightly larger than unity, the rate of energy dissipation in the tidal bore is proportional to $(Fr_1-1)^3$. For $1 < Fr_1 < 1.5$ to 1.8, the tidal bore is followed by a train of well-defined and quasi-periodic waves called undulations or whelps. This is the most common type of tidal bores on the Planet. Breaking bores are observed for $Fr_1 > 1.5$ to 1.8; these events imply a powerful tidal bore process only observed during king tide conditions and low river water levels: e.g., the Seine River and Qiantang River bores during equinox spring tides in September.

The bore front celerity U is proportional to $\sqrt{g \times d_2}$ where d_2 is the water depth immediately behind the bore. Hence the bore speed is related to the rate of rise of the sea level and to the tidal range. The tidal bores are stronger and advance faster during spring tide conditions and rarely occur during neap tides. Further the tidal bores are better seen during the dry season and low river flow periods when the initial water depth d_1 is small. As an illustration, the best periods to observe some tidal bores are the spring tides during the months of August to October for the Dordogne and Garonne Rivers, the months of March and September for the Baie du Mont Saint Michel, and the months of September and October for the Qiantang River in China. Note that the latter period coincides to the Chinese Moon festival

Equation (3) shows further that the bore shape and appearance may change rapidly in response to the estuarine bathymetry. In regions of deeper water (d_1 large), the bore may disappear when the local Froude number is less than unity, while it may strengthen in regions of shallow waters, shoals, and bars (d_1 small). In a given river section, the tidal bore may have a breaking bore appearance next to the bank in a region of shallow waters, and have an undular shape in a deeper section of the river channel.

The transverse shape of the bore is also related to the river bed topography. Since the celerity of the tidal bore is:

$$U = \sqrt{g \times d_1} \times (1 + \varepsilon) - V_1 \qquad (13)$$

with ε a function of the bore Froude number Fr_1, the bore front advances faster in deeper waters and slower above bars and shoals. In turn, some transverse variations in bathymetry may induce a non-linear transverse profile of the bore as illustrated in Figure 12.

Fig. 12 - Transverse profile of the Sélune River tidal bore (France) on 19 September 2008 - Note the "wavy" transverse profile of the undular tidal bore caused by the presence of shoals and bars

Some man-made interventions led to the disappearance of several tidal bores with often adverse impacts onto the eco-system: e.g., the mascaret of the Seine River (France) no longer exists after extensive training works and dredging, and the Colorado River bore (Mexico) is drastically smaller after dredging. Although the fluvial traffic gained in safety in each case, the ecology of estuarine zones were adversely affected. The tidal bores of the Colorado (Mexico), Couesnon (France) and Petitcodiac (Canada) Rivers almost disappeared after construction of upstream barrage(s). At Petitcodiac, this yielded the elimination of several diadromous fish species, including the American shad, Atlantic salmon, Atlantic tomcod, striped bass and sturgeon [37]. The Severn Barrage on the Bristol Channel would mark the disappearance of the Severn River tidal bore (UK).

The interactions between tidal bores and Humans are complicated and sometimes conflicting. The tidal bores can be dangerous and some bores have had a sinister reputation. Dozens of people were killed by flooding caused by the Qiantang River tidal bore near Hangzhou. In the past, the Seine River bore had a sinister reputation and numerous lives were lost over the centuries. The tidal bores of the Petitcodiac River (Bay of Fundy, Canada) and Colorado River (Mexico) were feared (e.g. [23]). In China, tidal bore warning signs are erected along the Qiantang River banks and a number of tragic accidents happen every year. The tidal bores affect adversely the shipping and navigation, as in Papua New Guinea (Fly and Bamu Rivers), Malaysia (Benak at Batang Lupar) and India (Hoogly bore). But, in the Severn River (UK), several commercial barges traded along the 'unnavigable' portion of the estuary between the 1930s and 1980s, using the strong flood flow immediately behind the tidal bore to shorten the upstream journey [48]. In China, the junks waited in the dry bore shelters along the dyke to ride upstream the Qiantang River behind the tidal bore. Today some sections of the Airbus A380 travel on barges on the Dee and Garonne River estuaries that are both affected by tidal bores. In the Garonne River, the author saw the barge carrying the A380 aircraft sections between Bordeaux and Langon following the tidal bore by less than 30 minutes to benefit from the strong flood tide current.

At the same time, the tidal bore can be a major tourism attraction. In China, the Qiantang River bore attracts more than 300,000 people each year for the Moon festival while the bore propagation is seen live on television by over 15 millions of television spectators. All the year around, tens of thousand of tourists come to see the tidal bore during spring tide conditions. The tidal bore of the Turnagain Inlet in Alaska is a feature of many organised tours, and its schedules are well-advertised. In the Bay of Fundy, Canada, thrill-seekers ride over the bore in inflatable dinghies, for example on the Shubenacadie River. In Europe, the Dordogne and Severn Rivers are the sites of well-known tidal bore surfing competitions (Fig. 13), while, in Brazil, surfing competitions are conducted on the Araguari River and Rio Mearim. In the early 1960s, the mascaret of the Seine River attracted more than 20,000 people during the week-ends.

Fig. 13 - Surfers on the Dordogne River bore in front of Port de Saint Pardon (France) on 30 September 2008 - Note the number of spectators on the bank in the background despite the overcast weather

Fig. 14 - Cultural impact of a tidal bore: "Rue du mascaret" ('Tidal bore street') in Langoiran, France (Courtesy of Dr Pierre Lubin)

5.3 Discussion

A tidal bore is an integral part of our environment and cultural heritage (Fig. 14). A number of local communities organise some festivals around the tidal bores: for example, the 'Pesta Benak' in Sri Aman (Malaysia), the 'mascaret de St Pardon' in September each year at Vayres (France) and the local town gathering along the Sélune River at Pontaubault in the Baie du Mont Saint Michel (France). Off course one cannot miss the traditional ceremonies in the Bhota Pagoda, Haining during the Chinese Moon festival along the Qiantang River (China). In the Baie de Seine (France), there is a lot of local and cultural history on the tidal bore ('mascaret') of the Seine River. It features in some poems and novels: e.g., the poem "Mes Premières Années de Paris" by Auguste Vacquerie (1877) and the novel "La Barre-y-va" by Maurice Leblanc (1931). Other tidal bores are introduced in some novels: e.g., the Amazon River tidal bore in "La Jangada" by Jules Vernes (1881) and "Tidal Rip" by Joe Buff (2003), the Hooghly River bore in the novel "The Sea of Poppies" by Amitav Ghosh (2008). The Qiantang River tidal bore features pro-eminently in the Chinese literature and folklore [16, 41].

The tidal bore is also the focus of a number of environmental groups and local residents. In Moncton (Canada), the Sentinelles Petitcodiac Riverkeeper has been active with the restoration of the tidal bore. In UK, several environmental groups have attacked the government's plans for the Severn Barrage that threatens the Severn River eco-system and its tidal bore. In the Baie du Mont Saint Michel (France), the Maison de la Baie du Mont Saint Michel (Vains) museum organises a year-long exhibition on the tidal bore in 2010.

6 TIDAL BORE SURFING

6.1 Presentation

The Qiantang River tidal bore was possibly the first bore to be surfed. During the South Song Dynasty (1127-1279 AD), some writings described the bore riders who were swimmers riding the bore front. These valiant swimmers were likely body surfing the front. In more recent times, several tidal bores have been surfed and some are the locus of regular surfing events (Fig. 1A, 1C & 13). These include the Severn River (UK) that has been surfed for over fifty years. In France, the Dordogne and Garonne Rivers have been surfed for more than a decade. More recently some surfing competitions were conducted in Brazil. So what is all the excitement about surfing a tidal bore? In the ocean, the surf lasts a few seconds to rarely over 30 s, and it is highly repeatable. With a tidal bore, it is all about timing and the surfer has one chance only. If he misses it, he has to wait 12 hours for the next bore. When the tidal bore arrives, the surfer attempts to match his speed with that of the bore front by paddling. Once the bore front starts to carry the surfer forward, the surfer stands on his feet and rides down the face of the first wave of the tidal bore, generally staying just ahead of the breaking part of the bore. When surfing an undular tidal bore, most surfers ride the first wave, but "*some sections* [...] *can have up to 12 well-formed/breaking waves behind the front, and if you loose the first wave, one can continue on the next ones. Sometimes, this is in purpose because the first* [wave] *is weak and small, or there are too many surfers; then we slow down to catch up the wave behind that may be a better one*." Practically the surfer must be quick because there are only a few seconds between successive waves.

Where is it best to surf the tidal bore front? In the non-breaking part or in the breaking section? The non-breaking section is often "*the most energetic where we can take the maximum speed for manoeuvres*". The junction between the breaking and non-breaking bore front, called the 'shoulder', has the steepest free-surface, with an average slope of about 25 to 30% (1:4 to 1:3), and locally more. It is often the preferred location for the experienced surfers: "*the junction of the breaking/undular section of the bore is* [...] *the steepest and most powerful section* [...] *most suited to surfing manoeuvres*" (Fig. 1A).

After the surfer looses the wave or the bore weakens, he becomes tossed by the whelps. Then it is the return to the bank and back to the starting point.

6.2 Surfer's speed

The surfer's skills on a tidal bore range from intermediate to expert by scientific standards [28]. A common problem for beginners is being unable to 'catch the wave'. Conversely the sign of a good surfer is his/her ability to be at the right place to catch the tidal bore, even a weak one. In comparison to an ocean wave, the experienced surfer may feel that the ride on a tidal bore wave is relatively easy. But it is not without danger. "*the main danger is the banks: there have been some broken arms and legs because of trunks, piles and branches*". The bore is sometimes reflected from the bank: "*it seems that the bore rebounds on the bank and moves across the river with a higher energy like a billiard pool ball*." The observation is consistent with the impact of a shock on the bank, and its reflection across the channel. This is a well known process in a supercritical open channel flow that is called a cross-wave or shock wave. Any flow disturbance including a change of direction or contraction induces the development of cross-waves propagating at the free-surface across the channel [29]; they are also observed in transcritical flows.

The aim of the tidal bore surfer is the distance and duration: how long can you ride the tidal bore, although other targets like power, innovation, and speed cannot be dismissed entirely. The surfer speed comes by drawing energy from the motion of the wave, by dropping down the face of the front hence gaining potential energy, and using subtle movements of the surf board on the water surface. The better surfers get more speed by some skilled pumping and turning actions. On ocean wave surfing, a few contributions give some valuable data [17, 26]. For both spilling and plunging breakers, the surfer speed on an ocean wave is linked with the wave breaking height H_b:

(14) $$V_s = 1.93 \times \sqrt{g \times H_b} \qquad \text{for ocean waves}$$

where the surfer speed V_s and the breaker height H_b are in m/s and m respectively [17].

Although some past observations in the Seine and Qiantang Rivers suggested tidal bore celerity up to 9 to 10 m/s, the most accurate field measurements give a bore celerity between 3 to 5 m/s in small to medium-size rivers. These values give a surfer's relative velocity (V_1+U) that is 2 to 3 times smaller than the largest surfer speeds observed on the ocean waves. For a surfer riding ahead of the bore front without maneuvering, his/her relative speed is a function the initial flow depth d_1 and bore Froude number Fr_1:

(15) $$V_s = U + V_1 = Fr_1 \times \sqrt{g \times d_1}$$ for a tidal bore

with Fr_1 always greater than unity while the bore front height (d_2-d_1) may be considered a proxy of the breaker height. Combining with Equation (3) it yields:

(16) $$V_s = \sqrt{\frac{g \times d_1}{2} \times \left(1 + \frac{d_2 - d_1}{d_1}\right) \times \left(2 + \frac{d_2 - d_1}{d_1}\right)}$$ for a tidal bore

Equation (16) is presented in Figure 15 for three initial flow depths between 1 and 2 m, and compared with ocean wave and tidal bore field data. Despite some scatter, the comparison shows that the tidal bore surfer speeds are typically slower than those of ocean wave surfing. For a comparable wave height, however, the surfer speed is comparable on ocean waves and tidal bores, and the combined data set of ocean wave and tidal bore surfing speeds yields:

(17) $$V_s = 1.90 \times \sqrt{g \times H_b}$$ for tidal bores and ocean waves

with a normalised coefficient of correlation of 0.96 for the 35 data samples. Equation (17) is compared with the data in Figure 15.

The experimental data and theoretical considerations show that the surfer speed on a tidal bore is relatively slow compared to the surfer speed on a large ocean wave, but the duration of the ride is several orders of magnitude longer. In October 2007, the surfers Eduardo Bagé and Patrick Audoy rode the Qiantang River bore for more than one hour [15]. Of interest, Equations (16) and (17) give an average surfer speed on the tidal bore in absence of maneuvering. In practice, the experienced surfers are not satisfied with a straight ride and prefer to maneuver around the 'shoulder', including carving, cutting back, even pumping when the bore front weakens. Their instantaneous speed is hence greater than that predicted by Equation (17).

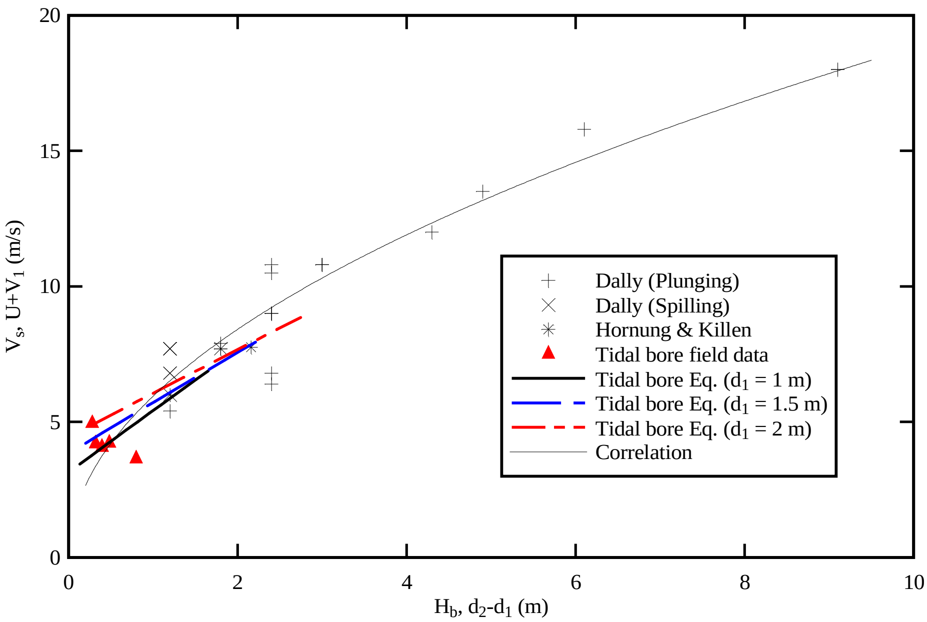


Fig. 15 - Average surfer speed on ocean waves and on a tidal bore: comparison between ocean wave surfing data (Hornung and Killen [26], Dally [17]), tidal bore celerity data, Equation (16) and Equation (17)

7 CONCLUSION

A tidal bore is a sudden rise in water elevation that may take place during the flood tide in a funnel shaped estuary with spring tidal conditions and a low freshwater level. The bore is a sharp front that propagates upstream into the river mouth and may travel several dozens of kilometres inland before vanishing. The presence of a tidal bore indicates some macro-tidal conditions (tidal range > 4 to 6 m) associated with an asymmetrical tide. The flood tide is usually shorter than the ebb tide period and the flood flow is much faster.

The tidal bore properties may be described by some simple theoretical considerations. A key feature of a tidal bore is its rumble noise that can be heard from far away. Some detailed measurements show that the sounds generated by a breaking bore have a low-pitch comparable to the sounds generated by bass drums and locomotive trains, and the dominant source of the rumble noise is the collective oscillations of the bubble clouds entrained in the tidal bore roller.

The detailed laboratory measurements show that a tidal bore is an enormous 'mixer' that stirs the matters and sediments, and the suspended matters are advected upstream into the upper estuarine zone. All the observations indicate that the tidal bores do have a significant effect on the natural channels and their ecology. The tidal bore affected estuaries are the natural habitats of several fish species, as well as the feeding grounds of larger predators like sharks, crocodiles, seals and whales. Importantly a tidal bore is the result of delicate balance between the tidal conditions, the freshwater conditions and the estuarine bathymetry, and this fragile balance can be easily disturbed: e.g., by a change in freshwater discharge, some variation in bathymetry (dredging, river training). Man-made interventions led to the disappearance of several tidal bores with often adverse impacts onto the eco-system.

The interactions between tidal bores and Mankind are complicated. Some bores are dangerous and have had a sinister reputation (Qiantang River, Seine River, Bamu and Fly Rivers) while hindering the local development and transportation. But the tidal bores can be some major tourism attractions like in Canada, China, France and UK. Several tidal bores are regularly surfed by kayakers and surfers in Brazil, France and UK. The surfers' aim is the distance and duration of the ride: how long can we ride the bore?

In terms of the community's interests, the study of tidal bores is clearly justified by their impact on a range of socio-economic resources. This impact may be direct as in the net upstream advection of sediment materials, or it may indirect as in the role of tidal bores in the reproduction and breeding of native fish species. A tidal bore is an integral part of our environment and cultural heritage, but it is an endangered phenomenon that can be too easily affected adversely by human interventions. The present contribution aims to foster the research and engineering progresses that are required to preserve this beautiful natural wonder and its cultural legacy. A tidal bore is a fascinating geophysical phenomenon for the surfers and kayakers as well as for the estuarine populations and tourists.

8 ACKNOWLEDGEMENTS

The author thanks the numerous people who provided him with valuable information. This contribution could not have been possible without their inputs.

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